

# Proposal for SHIPTRAP

## A CAPTURE AND STORAGE FACILITY AT GSI FOR HEAVY RADIONUCLIDES FROM SHIP

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### ABSTRACT

An electromagnetic trapping system to deliver very clean and cool beams of singly-charged recoil ions from the SHIP facility at GSI (SHIPTRAP) is proposed. The basic features of the facility are presented, including its estimated performance, and the physics interest in the facility is outlined.

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# 1. Introduction

With the recent developments of trap technology, several projects to couple electromagnetic and magneto-optical traps to various radionuclide-production facilities have been initiated around the world. Two European TMR Networks, EUROTRAPS and EXOTRAPs, have been created to coordinate developments in this field of research, including groups from Mainz, Stockholm, GSI, Leuven, ISOLDE (ISOLTRAP, MISTRAL and REX-ISOLDE), Jyväskylä, GANIL, Orsay, Munich and other laboratories. On-line neutral atom traps for accelerator produced radioactive isotopes are in operation at TRIUMF, Stony Brook, Los Alamos and Berkeley.

The interest in coupling traps to sources of radionuclides arises from the extremely small phase space in which radionuclides reside in a trap, from the long storage time, and from the extremely high purity that can be obtained by removing contaminant ions. The small phase space and the long storage time are prerequisites for high-accuracy experiments. The purification is very important since contaminants always plagued the production of exotic radioactive species. This separation into cool clean collections not only allows very sensitive and accurate experiments to be performed within the trap itself but also allows the collected radionuclides to be extracted from the trap and studied in a well-defined extremely low-emittance beam. Together, these possibilities open a wide range of physics applications.

The ISOLTRAP facility at ISOLDE/CERN [1], consisting of a Paul trap for accumulation of the 60-keV ISOLDE ion beam, a first Penning trap for isobar separation and a second one for high-accuracy mass measurements of short-lived isotopes, has demonstrated the potential of the ion trap concept at ISOL facilities. The present state of ion trap technology now allows the coupling of a trap system to ion beams of higher energy such as delivered by the SHIP velocity filter at GSI. A recent Letter of Intent on this SHIPTRAP project has been received positively by the Experiment Ausschluß of GSI [2]. A similar project has been started at a recoil separator at Argonne (USA) while at INS (Tokyo) a sextupole ion beam guide trap coupled to GARIS [3] has already been tested. The advantage such facilities will have is that they will enable the rich variety of physics experiments currently performed at ISOL facilities to be extended to isotopes for which target/ion source systems do not exist at ISOL facilities. The particular advantage that SHIPTRAP would have is the ability to extend these experiments to the transuranic isotopes. Thus SHIPTRAP will enable the application of refined ISOL techniques for the first time to isotopes with  $Z > 92$ , extending even to the superheavy elements of which many may have a sufficiently long half-life for trap technology.

This report focuses on the study of the transuranic isotopes, though research and development work on the SHIPTRAP project itself will almost certainly open possibilities at SHIP for studies in other regions of the nuclear chart. Furthermore, the experience gained with SHIPTRAP will be essential for future radioactive ion beam (RIB) facilities at GSI and elsewhere.

## 2. SHIP

SHIP is a kinematic separator for reaction recoils from thin targets irradiated by beams from the heavy ion linear accelerator UNILAC at GSI [4]. It is optimized for the separation of heavy elements produced by complete fusion of projectiles from  $A = 40$  to 80 with lead or bismuth nuclei. The typical target thickness is  $0.5 \text{ mg/cm}^2$ . The projectiles have energies close to  $5 \cdot A \text{ MeV}$  and typical time-averaged intensities of  $2 \times 10^{12} \text{ ions / s}$  to  $5 \times 10^{12} \text{ ions / s}$ . UNILAC has a repetition rate of 50 Hz with beam pulses having a duration of 6 ms.

The cross-sections for the production of trans-einsteinium elements are below one microbarn. For example, a cross section of  $3 \text{ } \mu\text{b}$  was measured for the 2n-channel of the reaction  $^{48}\text{Ca} + ^{208}\text{Pb} \rightarrow ^{256}\text{No}^*$  ( $Z = 102$ ), which corresponds to a production rate of 5 ions / s. Another recent experiment at SHIP has shown that the production of Rf ( $Z = 104$ ) using the reaction  $^{50}\text{Ti} + ^{207}\text{Pb} \rightarrow ^{257}\text{Rf}^*$  with evaporation of 2 neutrons is about 0.02 ions / s. As a further example, the reaction  $^{40}\text{Ar} + ^{208}\text{Pb} \rightarrow ^{248}\text{Fm}^*$  ( $Z = 100$ ), has cross sections calculated to be 30 nb for the 2n-channel, leading to an estimated production rate of about 0.1 ions / s. Of course, production rates for actinide isotopes of lower  $Z$  are several orders of magnitude higher, and those can be used for testing the SHIPTRAP facility for heavy-element research. Furthermore, SHIP has favorable production rates for many  $N \approx Z$  nuclei up to the very interesting case of  $^{100}\text{Sn}$  (see section 5.1.2.).

A new high-current injector will increase the time-averaged intensity of UNILAC by about two orders of magnitude (to  $4 \times 10^{14} \text{ ions / s}$ ), resulting in considerably higher yields of the reaction products. For the example of the reaction  $^{48}\text{Ca} + ^{208}\text{Pb} \rightarrow ^{254}\text{No} + 2\text{n}$ , the production rate could be as high as 250 ions / s. For  $^{100}\text{Sn}$  the production rate could amount up to 4 ions / s, which would be three orders of magnitude higher than the expected rate at the GSI fragment recoil separator FRS, even after the upgrade of the heavy ion synchrotron facility SIS.

However, these high-current beams, which will be accompanied by a reduction in the pulse duration to 1 ms, will have three orders of magnitude higher instantaneous intensity than the present. Using them will require the development of new heat resistant targets. For the actinide targets, which have a high melting point, and for irradiation with low-mass beams, which have low energy loss in the target, gas cooled targets as used at electron accelerators may be feasible, and will be investigated. Otherwise, non-solid targets will be necessary. Pulsed gas jets, ultrasonically evaporated material, clusters or plasma targets all seem to offer possibilities, the plasma target having the advantage of being material independent and universal but probably requiring the most extensive development.

From the wide range of possibilities it seems possible to develop targets that will make use of the increased beam intensities. However, such development will require a major research effort, involving extensive theoretical explorations of the

variety of exciting but relatively untried possibilities followed by testing of concepts with experimental set-ups.

It appears feasible to improve the separation quality of SHIP so as to guarantee sufficient background suppression for the increased beam intensity. However, at the same time the solid angle and momentum acceptance of SHIP should be increased, thereby increasing its transmission. This is especially important for the production of heavy elements with low-mass beams. Of particular interest in this regard is the SPIRAL spectrometer VAMOS at GANIL, which is being designed to have an acceptance solid angle of 125 msr compared to 2.7 msr for SHIP. This will be a test case for the adoption of a similar concept for SHIP.

In considering the stopping and trapping of the emergent beam of SHIP, the properties of this beam must be taken into account. Of particular importance are the purity of the beam, its spatial dimensions and its stopping range in a gas. These properties have been determined from observations of the scattered projectiles and from measurements of the profile of the beam and its energy degradation in foils.

### 3. Description of the SHIPTRAP facility

#### 3.1. Outline

Essentially, the proposed SHIPTRAP facility thermalizes the SHIP recoil ions in a noble gas from which they are then extracted and collected in a trap. The system for doing this is outlined in figure 1. It consists of a stopping chamber containing the noble gas, an extraction system to bring the stopped ions into a vacuum region, a preliminary trapping system to collect the ions in this vacuum region and to cool them into well defined bunches which are then extracted and injected into a final purification trap. This trap accumulates the ion bunches, filters out possible contaminants and further cools the collection to room temperature. This collection is then extracted on the demand of downstream experiments.

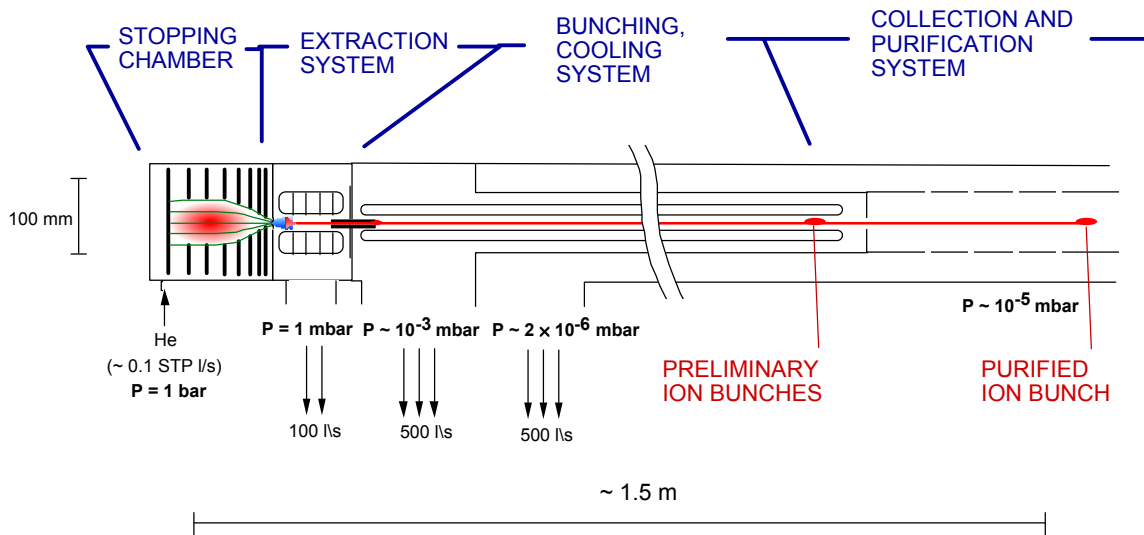


Figure 1. Overall configuration of SHIPTRAP.

The noble gas in the stopping chamber, at pressures ranging from one-tenth to one atmosphere, will thermalize the SHIP ions preferentially in the singly ionized state. An electric field, together with the gas flow, then guides the ions out of the chamber into the extraction system where they are separated from the gas. This system is a short quadrupole rod structure that confines the ions to its axis by an rf field while the noble gas is pumped away. An axial field within the structure guides the ions along the axis towards the bunching system. In the ion bunching system, a longer quadrupole rod structure immersed in a low pressure buffer gas, the ions are

trapped by a proper choice of buffer gas pressure and of axial dc and transverse rf fields. The purification system into which these preliminary bunches are collected is based on a Penning trap similar to the one used for this purpose at the ISOLTRAP facility at ISOLDE. In such a system the contaminating isotopes are very effectively suppressed due to the high mass resolving power of the cooling process that is employed which, depending on the trapping time, can reach  $M/\Delta M_{FWHM} = 10^5$ . The ion bunches delivered by this purification system will have extremely low emittances, thermal energy spreads and pulse durations of typically less than a microsecond, although bunches of longer duration could be extracted if desired. With current ISOL beam technology these bunches could be delivered at any energy desired up to about 60 keV.

In some cases it may be advantageous to use those SHIP ions that become neutral atoms in the stopping gas. These can then be re-ionized by resonance ionization spectroscopy (RIS) for delivery to the vacuum system. Such a scheme provides element selectivity, and for heavy elements isotopic selectivity as well, in the stopping chamber itself.

Details of the technical considerations that led to the configuration of SHIPTRAP, along with estimates of its expected performance, are given in a GSI report [5]. A summary of the results of that study will be included here.

### **3.2. The stopping chamber**

From the geometry of the SHIP beams and their stopping ranges, it is clear that the design of the stopping chamber, including the choice of stopping gas, is specific to a particular radionuclide of interest. Also the way they are prepared as ions (i.e. by direct stopping or by RIS) influences the design. For light radionuclides, it appears that helium would be the most appropriate gas, particularly for the RIS method. For the transuranic elements, because of the very thin windows that would have to be used for their transfer from the vacuum chamber of SHIP into the stopping chamber, it would be perhaps more appropriate to use argon at reduced pressure, despite its higher chemical reactivity compared with helium.

In the SHIPTRAP project it is the stopping chamber design that is expected to require the most sustained development program to achieve maximum performance from the facility. Indeed, a stopping chamber study program has already been started by the LMU München members of the collaboration. For now the preliminary studies indicate that, whichever gas is used, a majority (50 to 90%) of most radionuclides of interest could be contained within a spheroid of 20 mm diameter and 50 mm length.

The first practical problem that must therefore be addressed is that of containing and directing such an ion cloud toward, and through, an orifice leading the gas into a vacuum system. The processes involved in this transfer are the drag of ions through a gas by an electric field, governed by the ion mobility in that gas, and their diffusion in the gas while being dragged. Because it presented the most

challenging case, the technical study of these processes focused on the transuranic elements to mass number  $A \approx 300$  stopped in helium. This study led to an estimate that from 5 to 50% of the SHIP ions could be dragged into an orifice of 0.6 mm diameter in less than 8 ms. The main loss factors are the stopping efficiency, the diffusion loss, neutralization and the transport of the ions through the narrow orifice.

Short transit times are extremely important for many ions of interest. This is because, while all ions may have a high probability of being in a singly charged state when coming to rest in helium, many ion species are quickly neutralized by any interaction with an impurity molecule [6,7]. The gas should therefore be kept very clean and the transit times through the gas as short as possible. From general experience the transit time should be kept to less than 10 ms.

For optimal performance, the stopping chamber for ions produced by RIS ionization of stopped neutrals would have to be different from that for withdrawal of the radionuclides that come to rest as ions. Furthermore, the stopping chamber should be easily removable from the system for servicing and possible modifications as experience with the system grows.

### **3.3. The extraction system**

The purpose of the extraction system is to accept the ions delivered from the stopping chamber, to separate them from the in-flowing gas and to deliver them to a high-vacuum chamber which encloses the bunching system. A study of the flow of gases through orifices and of the processes involved in the extraction chamber led to the conclusion that a pressure of 1 mbar could be maintained in the chamber using a Roots blower of 100 l / s, and that at such a pressure the ions would follow the gas, at velocities considerably exceeding the speed of sound, until it formed a Mach disk about 12 mm from the orifice. After this the gas would disperse into an incoherent pattern at subsonic velocities. The problem then becomes that of separating the ions from the gas and directing them along the axis of the system for entrance into the higher vacuum system of the ion buncher. This is to be done by the well established technique of ion focusing by axiperiodic radiofrequency electric fields, as used in radiofrequency quadrupole mass filters. In the particular case here, the manipulations involved are to be carried out in the presence of a low pressure gas.

The manipulation of ions in low-pressure gases is a very old subject, dating back to the nineteenth century. The field of particular significance here is that of the use of non-uniform radiofrequency electric fields to guide ions along an axial system through such gases, the first report of such work being that of Teloy and Gerlich at Freiburg in 1974 [8]. Essentially, the trapping action of even-order radiofrequency electric multipole fields discovered by Paul and coworkers [9], and leading to the widely used quadrupole mass filter and the Paul trap, was applied for the first time to the containment of ions in an axial system in a deliberately introduced background of gas. Subsequent developments [10-12] have spanned chemistry and physics

applications, where the technique has become widely used for studies of the interactions of ions and molecules at pressures of about  $10^{-2}$  mbar.

Recent work [13] using radiofrequency quadrupole (RFQ) fields from a 4-rod structure with an axial electric field component have extended the studies of such structures to gas pressures above 1 mbar. It was shown that an axial field of less than 1 V/mm resulted in transport efficiencies through a 1 mm exit orifice of close to 100%, in overall transport times of less than 1 ms. Adapting these results to the SHIPTRAP scheme it seems that a 70% transport efficiency through the extraction chamber would be a conservative estimate, resulting in between 3% and 50% of the SHIP radionuclides being delivered to the ion buncher. The transport times through the extraction system would not add significantly to the time required to pull the ions out of the stopping chamber.

### **3.4. The ion cooling and bunching system**

The ion bunching system is necessary in order to provide efficient capture in the final cooling and preparation trap. This is because for optimum performance in the separation of contaminants this trap must operate on a relatively long cycle of up to 100 ms while for efficient capture it should be open for less than 100 microseconds.

As in the extraction system, the bunching system uses background buffer gas in a radiofrequency quadrupole rod system to constrain and damp the ion motion. The principal vacuum concerns here are providing enough gas to cool and catch the ions while at the same time preventing this gas from disturbing the operation of the subsequent purification system. A study of the possible gas flow rates into the bunching system indicated that a relatively modest turbopump of 500 l/s could maintain a pressure of about  $10^{-3}$  mbar in the bunching system and that at this pressure the operation of the purification system would not be disturbed. Also, at this pressure radiofrequency quadrupole fields could be used to constrain the ion motions to within a radius of about 1 mm from the axis while the buffer gas reduces the kinetic energies to levels at which the ions could be captured in an electric trap. The overall flight path over which this could be accomplished is estimated to be about one meter. The electric trap to be used in this bunching system is based on similar designs used to contain biomolecular ions in mass spectrometry for analytical chemistry [11]. It uses a combination of transverse confinement by radiofrequency quadrupole fields with axial confinement by dc potentials forming a potential well.

The overall capture efficiency for ions entering the bunching system is conservatively estimated to be 50 %, resulting in 1.5 % to 25 % of the SHIP radionuclides being collected. The captured cloud would typically be about 2 mm in diameter and about 4 mm in length. The overall time for the damping of the ion motion upon entering the buncher and their capture in the trap is estimated to be of the order of a millisecond, again not adding significantly to the time required for extraction of the SHIP ions from the stopping chamber.

Because of the small size of the collected bunches, extraction for delivery to the subsequent cooling and preparation trap should be straightforward, involving only the application of pulsed potentials of the order of 100 Volts. The resulting beam bunch should have a longitudinal emittance of about  $0.1 \pi\text{-eV}\cdot\mu\text{s}$ , with a similar transverse emittance (of the order of  $0.5 \pi\text{-mm}\cdot\text{mrad}$  at 60 keV). Because the damping and capture can be made to occur in less than a millisecond, extraction rates of 1000 Hz should be feasible. However, because the SHIP beam is itself pulsed at 50 Hz, this is probably the highest trap extraction rate that would be useful.

It should be noted that it is in the bunching system that the first limitation on beam intensity will appear. (Transport of ions in RFQ rod structures have shown no significant deterioration in performance at up to one nanoampere.) This is because the relatively gentle confinement fields that are employed will only resist the space-charge forces within the collected cloud for up to about  $10^5$  ions.

The very low emittances expected for the output of the bunching system suggest the possibility of using this output directly for collinear laser spectroscopy with fluorescence detection to study hyperfine structure and optical isotope shifts. The average beam current may not be very high but the expected beam quality is excellent and the pulsed character of the beam would allow strong suppression of background. The achievable resolution would be several orders of magnitude higher than that of resonance photoionization in the stopping chamber, which would use pulsed lasers and would suffer from Doppler and pressure broadening. For example, collinear laser spectroscopy could be possible in the very neutron-deficient region around  $^{100}\text{Sn}$  where the hyperfine splittings and isotope shifts are too small to be resolved by resonance ionization in a gas.

### 3.5. The collection and purification system

The collection and purification system is based on that used in the ISOLTRAP facility [1]. While designed around the specific requirements of providing cooled highly selected ions to a precision Penning trap for high-accuracy nuclear mass measurements, the system should be ideal for any other sort of experiment that requires collections of ions of extremely small phase space volume and of high purity.

The system is based on a long cylindrical Penning trap operating in helium as a buffer gas at about  $10^{-5}$  mbar. Such a system would achieve a mass resolving power of about 30 000 for the removal of mass isobars of  $A \approx 300$  ions. For nuclei far from the valley of stability this resolving power is sufficient to obtain an excellent isobaric background suppression. The Penning trap can be loaded efficiently by beam pulses of up to 20  $\mu\text{s}$  duration at any incoming ion energy up to about 100 eV.

Experience with the transfer of ions between traps at the ISOLTRAP facility indicates that the efficiency with which the ions in the linear trap can be delivered to the preparation Penning trap, should also be high. Assuming it to be 70%, the overall efficiency of collection of the SHIP radionuclides in the preparation trap would be 1%

to 15%. Because of the very small phase space volume of the collection, it should be easily possible to deliver all of it to experimenters.

## 4. The overall SHIPTRAP configuration

A summary of SHIPTRAP and its expected performance is given in figure 2.

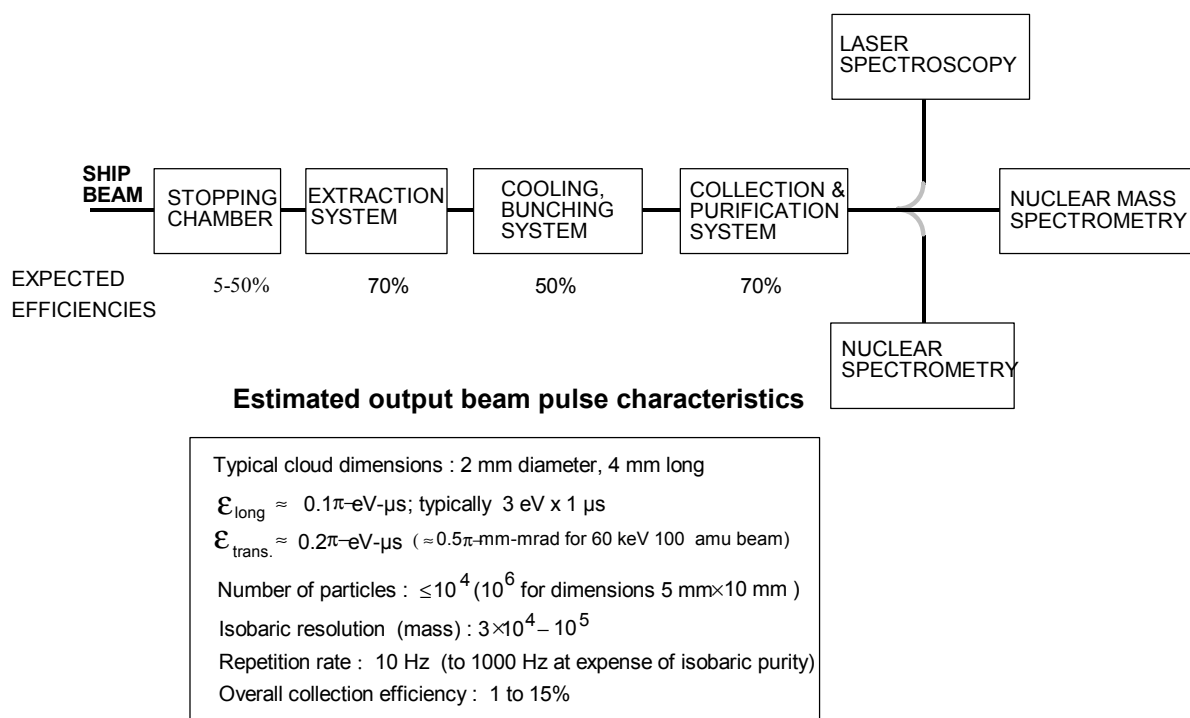


Figure 2. A schematic sketch of the planned SHIPTRAP facility.

As for the actual physical layout of SHIPTRAP, a horizontal configuration perpendicular to the SHIP beam line is suggested. A horizontal layout is preferred for the superconducting solenoid and its operation, while orthogonality to the SHIP beam is advantageous because the output beam of the SHIP facility is about twice as wide in the horizontal direction as it is in the vertical. Since the range straggle of the beam is probably comparable to, or even less than, the vertical dispersion, the ion cloud presented to the trap facility would have its greatest dimension in the direction of extraction toward the trap. This would ease the compression of the ion cloud onto the orifice, increasing only the time required to drag all of the ions to the orifice.

The layout of SHIPTRAP is sketched in fig. 3. This figure includes the coupling to SHIP and the 30 degree switch yard servicing different experiments.

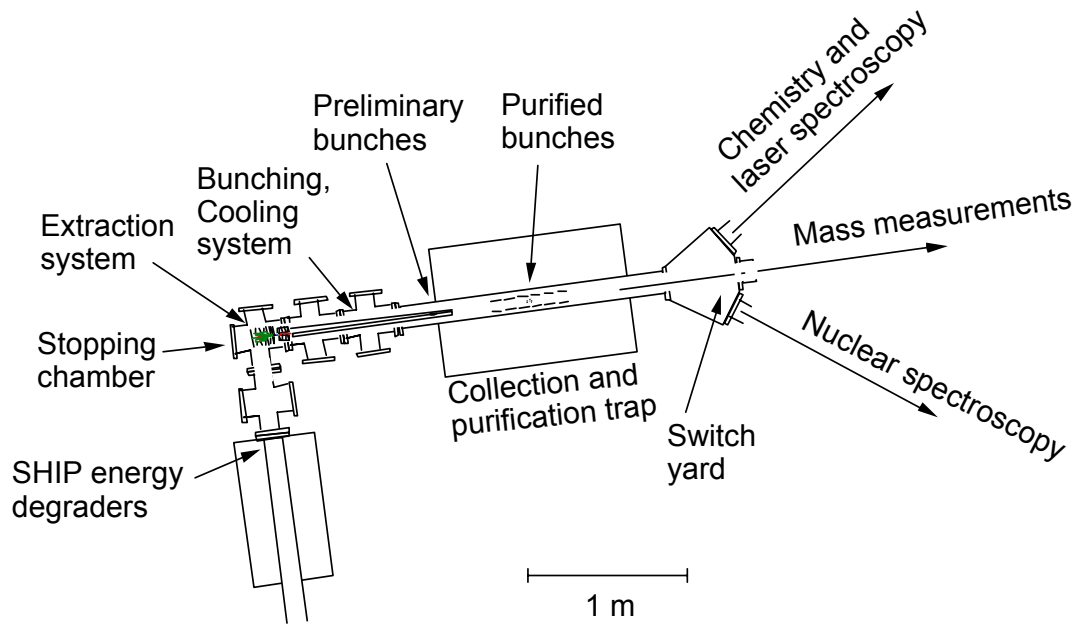


Figure 3. Overall configuration of the SHIPTRAP facility.

## 5. The scientific case for SHIPTRAP

The SHIPTRAP facility opens a great variety of new research opportunities in subatomic physics. Here we have selected a few areas in which specific experiments have already been proposed. In addition to these detailed proposals, we briefly mention three other possible lines of research. First, a set-up similar to SHIPTRAP could serve in the future at the Fragment Recoil Separator. Due to the much higher energy of the fragments, the stopping volume will be considerably larger, making an efficient extraction of the ions from the stopping chamber more difficult, in particular for short-lived nuclei. This drawback is compensated by the fact that the FRS offers high yields of both neutron-rich and neutron-deficient isotopes up to uranium. Second, the SHIPTRAP concept will open new possibilities for the development of a Radioactive Ion Beam facility at GSI for fusion or fragmentation reaction products. Third, it should be noted that a comparable device is planned for the fission fragment accelerator at the new Munich reactor FRM-II [14], where predominantly the synthesis of heavy elements will be studied.

### 5.1. Nuclear physics

#### 5.1.1. Nuclear mass measurements of trans-uranium isotopes

Investigations at SHIP of the heaviest elements has led to the discovery of a shell stabilized deformed region centered at  $Z = 108$  and  $N = 162$ . This region of enhanced stability against fission interconnects the trans-uranium elements and the predicted superheavy shell located at  $Z = 114$  and  $N = 184$  [15]. For the most neutron-rich isotopes of the elements up to hassium ( $Z = 108$ ) half-lives longer than one second were observed (for a review see [16]). This is in accordance with theory which predicts half-lives of seconds for a large number of isotopes, with maximum half-lives of the order of  $10^3$  seconds expected for even-even isotopes. These long half-lives open the possibility of research on heavy elements with ion traps.

The SHIP experiments have shown that the trans-rutherfordium elements located already in the region of macroscopic instability can exist only by microscopic stabilization [16]. The key question concerning the stability of the heavy elements is the amount of energy associated with the shell closure, which determines the height of the fission barrier and, ultimately, the stability against fission. By the use of an adequate macroscopic model the experimental shell correction energies can be obtained from ground state masses.

Specific properties that characterize superheavy nuclei are the influence of the large Coulomb forces between the great number of protons on the diffuseness of the proton surface, the high level density in the vicinity of the Fermi surface, and the large

shells with high angular momenta. Because of these effects these nuclei have complex structures. While this may lead to interesting phenomena such as shape isomerism, it makes predictions of the location and strength of the superheavy spherical shell closure very difficult. While macroscopic-microscopic models predict the superheavy shells for  $Z = 114$  and  $N = 184$ , self consistent calculations, performed in the framework of the Skyrme-Hartree-Fock method and the relativistic mean field approach, predict a spherical proton shell closure for  $Z = 120$  or  $Z = 126$ . An accurate knowledge of the masses of the available superheavy nuclei would help in selecting the best model for such predictions.

In the present experiments masses of superheavy nuclei are extracted from the  $Q_\alpha$ -values of decay chains leading to isotopes with known masses. However, this procedure is hampered by the fact that it relies on the general assumption that it is ground-state to ground-state transitions that are observed, which, in general, is only justified for even-even nuclei. In addition decay chains of the increasingly heavier elements and neutron-rich isotopes in the interesting region near the  $N = 162$  shell closure end in daughters with unknown decay properties. As a consequence the commonly used correlation technique fails, making the assignment of such species very difficult. As a further limitation of this method, all presently known even-even isotopes of rutherfordium ( $Z=104$ ) decay almost exclusively by spontaneous fission. So far, only for the relatively neutron deficient  $^{256}\text{Rf}$  has a small  $\alpha$ -branch of  $b_\alpha = (0.0032 \pm 0.0017)$  been reported [17], allowing a direct connection of the masses of the  $T_z = -24$  isotopes of  $Z \geq 104$  to the masses of lighter elements.

In figure 4 we compare the masses derived from this connection to recent predictions. Here Smolanczuk and Sobiczewski [18] and Myers and Swiatecki [19] predict similar values. Their masses are higher than the experimental values, by less than 0.7 MeV, while Möller et al. [20] predict masses that are lower by roughly one MeV. For all three predictions a slight trend can be seen to increasing deviation from experimental values with increasing mass. It seems clear that more, and better, experimental mass values are needed to test theoretical models, especially for the more neutron-rich nuclei located close to the predicted neutron shell at  $N = 162$ . Such data would also lead to a better prediction of reaction Q-values, which is crucial for heavy element production. (Recent SHIP experiments [16] have shown that the production of nuclei with  $Z \geq 108$  as residues of neutron evaporation from reactions in Pb and Bi targets is limited to narrow excitation energy windows.)

Observations have also suggested the existence of isomeric states, decaying by  $\alpha$ -emission, in several isotopes of elements with  $Z \geq 104$  [16]. However, a detailed study has been performed only for  $^{257}\text{Rf}$ , where the isomer was attributed to an  $11/2^-$  state at  $E^* = 118$  keV [17]. Accurate mass measurements would yield the excitation energies of such isomeric states for comparison with theoretical calculations of the level structure [18]. This would also give a better understanding of the single particle levels and thus improve predictions concerning nuclear shells.

A high-resolution Penning trap mass spectrometer coupled to the SHIPTRAP facility would be ideal for studying these problems. This would allow direct mass

spectrometry of heavy actinide and transactinide isotopes, provided the background of transfer products can be sufficiently suppressed.

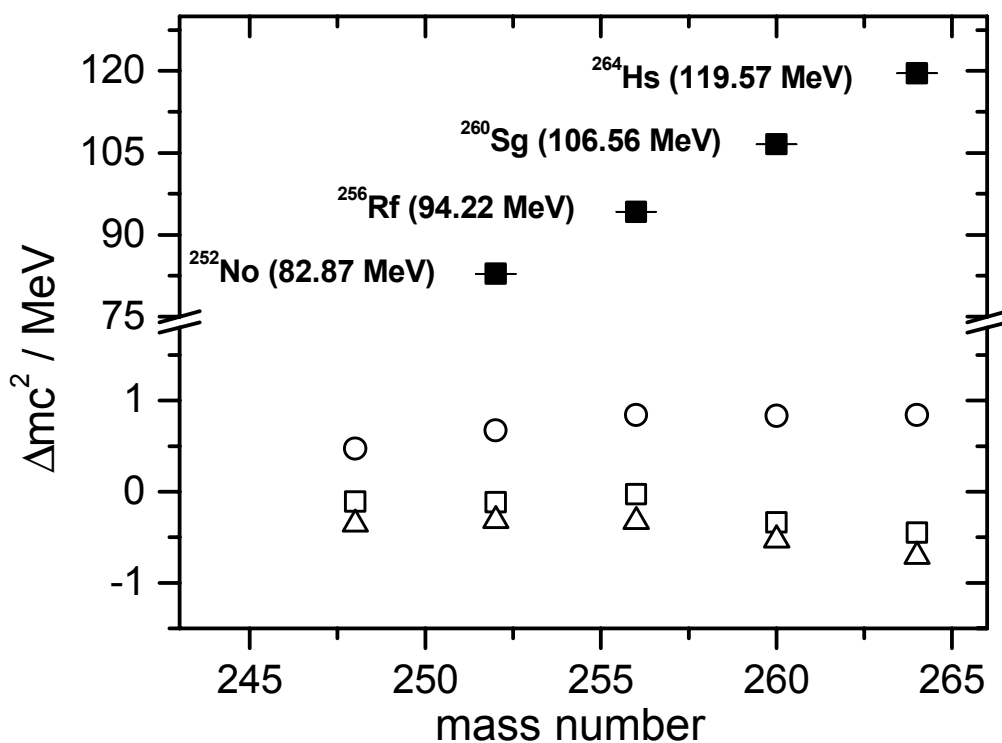


Figure 4. Comparison of experimental and calculated mass-excess values. Upper part :  $\blacksquare$  : experimental mass-excess values. Lower part :  $(\Delta m_{\text{exp}} - \Delta m_{\text{calc}})c^2$  according to [18] (□), [19] (Δ) and [20] (O).

### 5.1.2. Nuclear mass measurements and spectroscopy of $N \approx Z$ nuclei

The study of properties of doubly magic nuclei and their neighbours is a very important test of the ability of nuclear models to predict and describe underlying shell structures. In particular, the high intrinsic symmetry due to the simultaneous closure of identical shells for protons and neutrons ( $N = Z = 50$ ) in  $^{100}\text{Sn}$  leads to extraordinary properties for this heaviest self-conjugate nucleus synthesized so far. Particularly interesting features are the occurrence of charged-particle ground-state radioactivity in nuclei slightly heavier than  $^{100}\text{Sn}$  and of fast  $\pi g_{9/2} \rightarrow \nu g_{7/2}$  Gamow-Teller (GT) transitions in the  $^{100}\text{Sn}$  region, which allow the exploration of nuclear core polarization by comparing the experimental GT strength to predictions obtained by large-scale shell-model calculations.

Most of the experimental progress in studying nuclear ground-state properties near  $^{100}\text{Sn}$  has been obtained by using heavy-ion induced fusion-evaporation reactions. Milestones along this progress are:

1. The first mass measurement of  $^{100}\text{Sn}$  at GANIL [21], even though the limited accuracy ( $-57.770 \pm 0.300(\text{syst.}) \pm 0.900(\text{stat.})$  MeV) achieved in this experiment is not sufficient to allow a conclusive comparison with theory.
2. The investigation of the island of proton and  $\alpha$ -radioactivity above  $^{100}\text{Sn}$ .
3. The  $\beta$ -decay studies of  $^{94}\text{Ag}$  [22], the heaviest  $N = Z$  odd-odd nucleus known to date,  $^{101}\text{Sn}$  [23], the only single-nucleon nucleus around  $^{100}\text{Sn}$  with known properties, and  $^{97}\text{Ag}$  [24] and  $^{103}\text{In}$  [25], for which in both cases the complete GT strength distribution was measured.
4. The search for cluster radioactivity of  $^{114}\text{Ba}$  [26].

GSI has been a leading contributor in this field. SHIP has been used to study the proton radioactivity of  $^{109}\text{I}$  and  $^{113}\text{Cs}$  (item 2) and most of the other recent data of items 2 to 4 stem from research at the GSI on-line mass separator.

More recently, experiments based on fragmentation reactions have contributed further to nuclear-structure studies in the  $^{100}\text{Sn}$  region.  $^{100}\text{Sn}$  itself was identified at the projectile fragment separator FRS of GSI by using a 1.1-A GeV  $^{124}\text{Xe}$  beam [27] and at GANIL by using a 63-A MeV  $^{112}\text{Sn}$  beam [28]. The GSI experiment even yielded a value of  $(0.9^{+0.6}_{-0.3})$  s for the half-life of  $^{100}\text{Sn}$  [29].

However, for a meaningful determination of the GT strength distribution of the decay of  $^{100}\text{Sn}$ , accuracy is required for the experimental half-life, the  $Q_{\text{EC}}$  value, and the  $\beta$ -intensity distribution. It remains an open question whether the required accuracy, which has been reached for the cases of  $^{97}\text{Ag}$  and  $^{103}\text{In}$  mentioned above, will be obtained in the  $^{100}\text{Sn}$  experiment presently planned at the FRS using  $^{112}\text{Sn}$  fragmentation.

On the other hand, it has been demonstrated by the ISOLTRAP experiment at ISOLDE that Penning traps can be used for mass measurements reaching a mass resolving power  $M/\Delta M$  up to  $10^7$  and accuracies better than  $10^{-7}$  [1]. The half-life of

$^{100}\text{Sn}$  is long enough to fully exploit these capabilities. Compared to the present accuracy for  $^{100}\text{Sn}$  this would give an improvement by about two orders of magnitude.

However, to now, sufficient background suppression of the isobaric isotopes ( $^{100}\text{Ag}$ ,  $^{100}\text{Cd}$ ,  $^{100}\text{In}$ ) and neighbouring masses, produced at much higher rates than  $^{100}\text{Sn}$ , could only be achieved via the FRS. Fusion reaction based facilities, such as SHIP, have suffered critically from these contaminations, thus preventing spectroscopic studies despite the higher production rates. For SHIPTRAP we therefore need to consider the total background produced in the reaction  $^{58}\text{Ni} + ^{50}\text{Cr}$ , including not only isobars but all produced isotopes ( $91 \leq A \leq 104$ ). From the experimental cross sections for  $^{100}\text{Ag}$ ,  $^{100}\text{Cd}$ ,  $^{100}\text{In}$  and  $^{100}\text{Sn}$  [21] and cross section extrapolations using statistical model calculations (HIVAP, PACE), we conclude that it is necessary to suppress  $2 \cdot 10^6$  unwanted ions for each  $^{100}\text{Sn}$  ion.

In this respect results from ISOLTRAP look promising in that no deterioration has been observed in the mass resolution of its purification trap due to space charge effects from  $10^4$  unwanted ions. It is expected that by enlarging the axial extent of the cooling region within the trap, or by dividing the cooling into a two-stage process (still within a single solenoid), a suppression factor of  $10^6$  should be achievable. Moreover the background can be reduced by two orders of magnitude by using purifying procedures in the measurement trap itself. Another possibility for reducing background is to operate the buncher (see section 3.4) with a moderate resolution of  $\Delta M/M = 100$ . In this case only the isobaric background has to be suppressed by the purification trap, requiring an undeteriorated operation in the presence of about  $10^5$  unwanted ions. Furthermore, the large mass differences between isobars far from stability are advantageous.

At the present SHIP facility a reaction cross section of  $1 \mu\text{b}$  corresponds to a yield of 1 ion / s [30]. With regard to  $^{100}\text{Sn}$ , the measured cross section of about 40 nb [21] will result in 0.04 ions / s or about 3500 ions / day. The estimates given in [31] for the FRS at GSI are 1 ion / day, while the GANIL cyclotrons produce 10 ions / day and the GSI on-line mass separator 1200 ions / day. Due to the 50 Hz UNILAC beam structure each beam pulse, on the average, produces  $8 \times 10^{-4}$   $^{100}\text{Sn}$  ions and  $1.6 \times 10^3$  background ions. With an envisaged delay time in the buffer gas cell / RFQ system of less than 10 ms and a purification trap operation frequency of 50 Hz a single beam pulse would correspond to a single trap filling. Thus even an intensity upgrade by two orders of magnitude (see section 2) will result in less than  $10^6$  ions simultaneously filling the trap. As mentioned above this number is still acceptable, while the  $^{100}\text{Sn}$  yield would be increased to a remarkable number of  $3.5 \times 10^5$  ions / day, which is three orders of magnitude higher than expected at the FRS after the UNILAC and SIS upgrades.

We plan to demonstrate the capabilities of this concept in a prototype experiment aiming at the heaviest doubly magic  $N = Z$  nucleus  $^{100}\text{Sn}$  [2]. Since masses and other ground-state properties of nuclei in the vicinity of  $^{100}\text{Sn}$  are mostly unknown, it will be also important to measure them in the same experiment, where they are produced as a dominant 'background' to  $^{100}\text{Sn}$ .

Below  $Z = 50$  the masses of nuclei near the proton drip line are important for the understanding of the rp-process [32], which could produce nuclei up to  $^{96}\text{Cd}$  and  $^{100}\text{Sn}$ . Calculations concerning this process until now have had to rely on theoretical mass models whose predictions differ sometimes by more than 1 MeV. Mass measurements with a precision better than 100 keV would be of great help.

Besides mass measurements in a high-resolution trap, a broad field of nuclear decay spectroscopy can be envisioned. The large Q-values of the  $\beta$ -decays, with corresponding high  $\gamma$ -ray energies (up to 10 MeV), can be studied with very efficient  $4\pi$   $\gamma$ -arrays like MINIBALL with the aim of obtaining complete GT strength distributions. Closely related would be experiments on proton radioactivity, for example  $^{105}\text{Sb}$ , or on possible cluster radioactivity in  $^{114}\text{Ba}$ . For both cases, the charged-particle decay mode represents only a small fraction of the total decay rate and so the half-life is not too short. Once charged-particle detectors are available in a Penning trap subsequent to SHIPTRAP (see section 5.1.3) the observation of direct or  $\beta$ -delayed charged-particle emission could be applied to the study of nuclei such as  $^{94}\text{Ag}$  [22] and  $^{101}\text{Sn}$  [23].

### **5.1.3. Precision nuclear spectrometry**

SHIPTRAP would be an excellent facility for precision nuclear spectrometry of short-lived nuclei. For such studies the bunches of radioactive ions would be delivered to a subsequent Penning trap, in a fashion similar to that of the ISOLTRAP system for mass measurements. However, the Penning trap employed here would be a simple containment device, requiring as high a magnetic field as possible but with minimal requirements on magnetic field uniformity and electric field shape. Such a trap would provide a radioactive “source” of a particular nuclear species that is completely free of the absorption and backscattering problems created by the backing material, problems that have plagued all previous high-precision nuclear spectroscopy on nuclear decays.

Furthermore, because of the high magnetic field of such a trap, an array of beta, gamma and charged-particle detectors can be configured, as shown in figure 5, so that each detector presents a very clean spectrum of the activity it is meant to observe, suffering little background from the others. In such a configuration, the betas from the source are channeled in a column of less than 10 mm in diameter to a solid-state detector positioned far enough from the source to suffer little from gamma and x rays. The gamma detectors, being annular with a large enough inner diameter to escape impacts with the betas, detect only gammas. Meanwhile, a square array of thin surface-barrier detectors surrounding the source can detect charged particles, such as beta-delayed protons, alphas and, possibly, alpha clusters such as  $^{12}\text{C}$ , which all have sufficient magnetic rigidity to reach them. (Because of the magneto-resistance of semiconductors it is important to have the crystal axis of the beta and

gamma detectors aligned properly with the magnetic field, and to increase the charge collection time so as to achieve optimum detector resolution. It has been demonstrated that if these measures are taken good detector performance can be achieved from intrinsic germanium in a high magnetic field [33].)

The simplest use for such a system would be for the observation of the beta spectrum of short-lived nuclei. With accurate knowledge of the decay scheme of the nucleus such observations can yield the binding energy of the nucleus to within several keV [33]. If this is combined with observation of coincidences in the detection of betas and gammas then even unknown decay schemes can be resolved. Of particular interest for such studies would be the non-analog admixtures to superallowed  $0^+ - 0^+$  decay modes, which would indicate how closely the nuclear forces of protons and neutrons mimic each other.

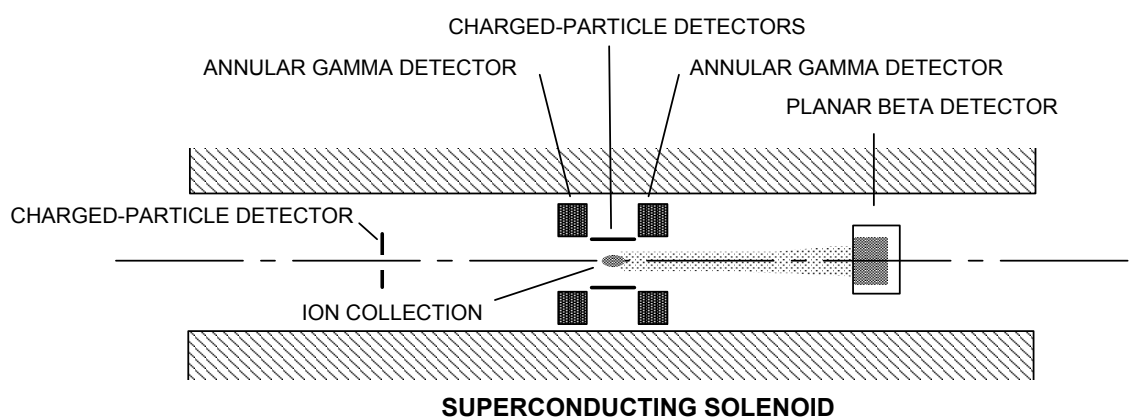


Figure 5. Schematic of a precision nuclear spectrometer for SHIPTRAP. The housings for the annular gamma detectors and the surfaces of the charged particle detectors surrounding the radioactive ion collection (four in quadrant formation) form the electrodes of the trap.

By including the observations of charged particles, studies can be made on beta-delayed proton emission, alpha decay and decay by cluster emission. Here the absence of source mounting material is especially important, allowing the observation of the particle emission spectra with unprecedented resolution and accuracy. Of particular interest would be the line-shape of the proton spectrum in beta-delayed proton emission, which could lead to basic information on the weak interaction involved.

Furthermore, studies can be done on particle emission that is in coincidence with the emission of gammas and/or betas, yielding important information on the overall decay scheme of such nuclei and thereby providing stringent tests of nuclear models that would lead to such decay. Finally, by placing a thin particle detector on the axis of the trap but opposite from the beta detector, and with a small hole to allow the delivery of the radioactive ions to the trap, one can study the recoil of the nucleus

due to beta emission. This would provide even further tests of the dynamics involved in the decay of these very interesting nuclei.

A massless radioactive sample inside a Penning trap would also be an ideal source for electron spectroscopy. Systems where the activity under study is implanted in supporting material destroy the inherent resolution of the electron spectrum. Furthermore, systems where the activity is itself implanted in a semiconductor detector suffer from the summation, inside the crystal, of the signals from the alpha or beta particles with those of the much weaker signals from the electrons. These problems are completely avoided in the trapping system proposed here.

Moreover, the intense magnetic field of the trap would collimate any electrons emitted from the source into a very narrow beam. High-resolution solid state detectors and bolometer detector systems for these electrons could therefore be very small and easily cooled, enabling resolutions of sub-keV. This would allow a precise study of the energies and intensities of conversion and Auger electrons emitted by the radioactive sample in the trap, allowing high-resolution measurements of electron energies out to the outer shells.

Of particular interest is electron spectroscopy of high-Z nuclei. Electron capture and internal conversion are often the dominating nuclear decay processes in the trans-uranium region and the high sensitivity of the various K/L and L/M electron intensity ratios to the multipolarity of the transition offers a valuable tool for spin and parity determinations. L-conversion is especially important in this region of the nuclear chart, necessitating an energy resolution sufficient to determine the relative intensities of the L branches. As a representative example, the L-shell binding energies of Rf ( $Z=104$ ) are 30.88, 29.99, and 22.91 keV and those of the M-shell are 8.16, 7.74, 6.01, 5.34, and 5.01 keV. A gamma-transition with an energy of 56 keV has a total E2 conversion coefficient of 590 and is dominated by L2 and L3 contributions. The Auger yields for the L-shell in Rf are of the order of a few tens of percent. Thus transuranic nuclei give a very vivid display of the nature of their decay processes in the pattern of atomic electrons they radiate.

#### 5.1.4. Nuclear fission reaction studies

A careful study of nuclear fission gives a deeper insight into the influence of shell effects on nuclear dynamics. Fission-fragment mass distributions and total kinetic energies can vary significantly from one nucleus to another. For example,  $^{256}\text{Fm}$  shows a double-humped mass distribution, similar to that for the lighter actinides, while  $^{258}\text{Fm}$  exhibits a narrow, symmetric mass distribution and exceptionally high total kinetic energies. This finding has been attributed to the influence of the double shell closure in  $^{132}\text{Sn}$  on the fission process (e.g. [34-35]). Another transition from asymmetric to symmetric fission has been observed around  $^{226}\text{Th}$  [36]. Knowledge of the systematics of the fission properties of nuclei would lead to an improved understanding of nuclear-structure effects on nuclear dynamics

Unfortunately, fission properties have been determined for only a fraction of the known fissile nuclei (figure 6). Most of the available information has come from studies of reaction induced fission which, in the past, have involved reactions in target nuclei. Recent studies at GSI [36] have considerably expanded our knowledge of such fissioning processes by having the fission induced within a projectile ( $^{238}\text{U}$ ) and studying the products as secondary beams emerging from the target. However, both techniques are restricted to nuclei for which sufficient material is available, effectively limiting such studies to  $^{238}\text{U}$ , or lighter, nuclei.

For transuranic nuclei, spontaneous fission offers the best possibility to study low-energy fission. Up to now experiments on spontaneously fissioning transuranic nuclei have been performed exclusively at Berkeley [37-39], and table 1 reveals that many of the spontaneously fissioning nuclei have not yet been studied. Most of these can easily be produced by heavy-ion fusion reactions and separated by SHIP. As has been proven by the great success of SHIP in heavy-element identification, the combination of cold-fusion reactions with a recoil separator provides very good conditions for research on the spontaneous fission of such elements. However, up to now no experimental set-up designed for this purpose has been available. In previous experiments at SHIP the nuclei were implanted into a surface-barrier detector but, due to the implantation depth, the signals of the two fission fragments could not be separated. Thus, while spontaneous fission half-lives could be measured and rough kinetic energies of fission fragments from  $^{256,258}\text{Rf}$  could be deduced [40], no fission-fragment mass distributions could be determined.

The experimental method which is best suited to study the fission properties of spontaneously fissioning nuclei which are only available in small numbers is to measure the energies of the two fission fragments in two opposite detectors in a close geometry. This "double-energy" method allows the determination of the mass distribution prior to neutron evaporation and of the total kinetic energy released in the fission process. However, for this method to be applicable the evaporation residues have to be deposited between two energy-sensitive detectors, avoiding any implantation in either detector.

Because of the very low energies at which it can deliver reaction products, SHIPTRAP will be well suited to provide such a deposition. For elements with sufficient production rate, most of the spontaneously fissioning nuclei to be produced at SHIP can be identified from their excitation function. Therefore, the operation of the collection and purification system may not be necessary, making fission experiments perhaps one of the first, and easiest, applications of the facility.

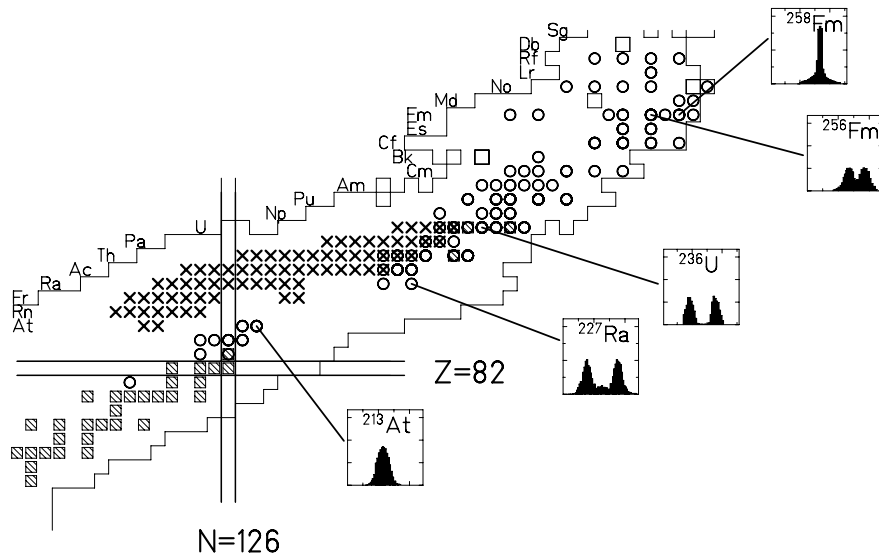


Figure 6. Overview on the present knowledge on low-energy fission. Circles: nuclei for which mass or charge distributions have been observed by conventional techniques. Crosses: nuclei for which charge distributions have been determined from secondary beams in a recent GSI experiment [36].

For further studies, the full functionality of SHIPTRAP may be important. Independent mass identification in the trap together with the registration of the fission fragments will allow studies to be carried out for single atoms. This would be very important for cases where the alpha-decay branch of the reaction products may be too weak to allow genetic identification. The application of additional detectors would also allow extensions of the experiments to the determination of neutron multiplicity and the observation of emitted gamma rays.

There are a few requirements and restrictions to be taken into account. For a statistically significant result, at least 1000 events should be registered. For low

production cross sections, the two opposite detectors should therefore be mounted rather close to each other so as to obtain a high detection efficiency. Yet the deposition of the residues on the center of one detector should not be hindered, perhaps requiring that one of the detectors have a hole permitting transport through it for deposition of the surface of the opposite detector. The transport time of the SHIPTRAP system also provides another restriction, allowing only the study of nuclei with a half-life of several milliseconds or greater. However, table 1 shows that this restriction excludes only a small fraction of the nuclei to be investigated.

Altogether, the excellent conditions for producing and separating heavy nuclei at GSI combined with a SHIPTRAP facility that would allow gentle deposition of such radionuclides on a silicon detector will open up unique possibilities for nuclear-fission studies on the most heavy nuclei. It is possible that the fission properties of more than a dozen heavy nuclei may be observed for the first time. Together with the successful application of secondary beams from the fragmentation of  $^{238}\text{U}$  this will make GSI one of the most advanced research institutes on nuclear fission.

Nucleus	$t_{1/2}$	Nucleus	$t_{1/2}$
$^{242}\text{Fm}$ (?)	0.8 ms	$^{255}\text{Rf}$	1.5 s
$^{244}\text{Fm}$	3 ms	$^{259}\text{Rf}$	3 s
$^{250}\text{Fm}$	30 m	$^{255}\text{Db}$ (?)	$\approx 1.6$ s
$^{252}\text{Fm}$	25.39 h	$^{256}\text{Db}$	$\approx 2.6$ s
$^{255}\text{Fm}$	20.1 h	$^{257}\text{Db}$	1.3 s
$^{245}\text{Md}$	0.9 ms	$^{261}\text{Db}$	1.8 s
$^{247}\text{Md}$ (?)	$\approx 0.2$ s	$^{262}\text{Db}$	34 s
$^{250}\text{No}$ (?)	0.25 ms	$^{263}\text{Db}$	27 s
$^{260}\text{No}$ (?)	106 ms	$^{258}\text{Sg}$	2.9 ms
$^{261}\text{Lr}$	39 m	$^{260}\text{Sg}$	3.6 ms
$^{253}\text{Rf}$	45 $\mu\text{s}$	$^{263}\text{Sg}$	0.9 s
$^{254}\text{Rf}$	23 $\mu\text{s}$	$^{264}\text{Hs}$	0.45 ms

Table 1. Compilation of spontaneously fissioning nuclei with  $Z \geq 100$  ([16] for  $^{264}\text{Hs}$ , [17] for  $^{253,254}\text{Rf}$  and  $^{258}\text{Sg}$ , [41] for all other isotopes) for which no mass distributions of fission fragments have been measured. Question marks refer to ambiguous identifications.

## 5.2. Chemistry

One of the most fascinating studies of the heaviest actinides and the transactinides concerns the influence of increasingly strong relativistic effects on the valence-electron configuration of the atom and its consequences on chemical behaviour. At present, the most advanced method for the investigation of the properties of trans-einsteinium elements is chemistry on single atoms in aqueous solutions [42]. This technique has already provided detailed chemical information for  $Z = 105$  and, most recently, for  $Z = 106$  [43]. The aim of such experiments is to compare the chemical properties with homologous elements. For example, the element  $Z = 105$  (dubnium) is the chemical homologue in the column vanadium ( $Z = 23$ ), niobium ( $Z = 41$ ) and tantalum ( $Z = 73$ ). However, it is well known that relativistic effects gain an increasingly important role for the heaviest elements around  $Z = 100$  and consequently the atomic and chemical properties of these elements may not behave as expected from the periodicity. Qualitatively, the relativistic effects are caused by a shrinkage of the wave functions of inner- and outer-shell s- and  $p_{1/2}$ -electrons which, in turn, also influences the binding energy of all valence electrons. In the transactinide region these 5f-, 6d-, 7p- and 7s-electrons are energetically close to each other. Quantitatively, the valence electron configurations of these elements can be predicted by multi-configuration Hartree-Fock-Dirac calculations and other methods [44-46], but these ab-initio calculations are complicated and have limited accuracy. The results therefore need to be checked by experiments.

So far, chemical experiments of the heaviest actinides and transactinides have been aimed at determining which chemical compounds are formed in a given chemical environment and which chemical properties these compounds have. Experiments were always designed such that important quantities, like stability constants or distribution coefficients, were determined in chemical equilibrium. At SHIPTRAP, reaction studies of trapped ions with small amounts of a reactive gas in an ion trap would allow kinetic studies by investigating the loss rate of an ionic species from the trap. In addition, this may give access to chemical studies of short-lived isotopes of the heaviest elements, which is mandatory for chemical studies in cases where all known isotopes of a given element are short-lived. Traps would also provide access to oxidation states which are not available to chemical investigations with current methods. This is of importance because, for the heaviest elements, lower oxidation states are predicted to play an important role. One of the deficiencies of the "traditional" methods in heavy-element chemistry is that the form of the chemical compound is not directly measured but only deduced from analogies in the chemical behaviour. Mass measurement of the chemical compound would give direct information as to what species is formed in the chemical reaction.

By employing charge exchange on the delivered ions, SHIPTRAP would provide the possibility of studying atomic lawrencium ( $Z=103$ ), the heaviest actinide

element. This would provide a critical test of multi-configurational Hartree-Fock-Dirac calculations. For lawrencium, theory predicts a ground-state configuration of  $7s^7p$  instead of  $6d7s^2$ . A Stern-Gerlach type experiment - deflecting an atomic beam of lawrencium in an inhomogeneous magnetic field and determining the magnetic moment by the number of multiplets in the atomic beam - would allow these two ground-state configurations to be distinguished. This technique may also be applicable to element 104, rutherfordium, where similar questions are under discussion. An experimental approach using a He-jet transport system to provide such atomic beam [47] has been abandoned because of technical problems.

The SHIPTRAP facility could also be used to study gas phase ion chemical reactions, which occur between ions and admixtures such as  $O_2$ ,  $H_2O$ ,  $CO_2$ ,... to the buffer gas in the stopping chamber. Such studies would provide information about electron configurations and the size of valence orbits of the ions, as has been demonstrated in investigations of the reactivity of transition element ions such as  $Hf^+$ ,  $Ta^+$  or  $W^+$  with  $O_2$ ,  $H_2O$ ,  $CH_4$ ,  $C_2H_6$  and  $CO_2$  [48,49]. For the experiments on heavy elements, advantage will be taken of the fact that a large fraction, about 87%, of the fusion reaction products delivered from SHIP come to rest in the stopping chamber of SHIPTRAP as ions. It is expected that the investigations can be extended to short-lived transactinides with  $Z > 106$  and  $T_{1/2} < 100$  ms, which are out of reach to gas chromatographic methods.

### 5.3. Optical spectroscopy of trans-einsteinium elements

An even more critical test of ab-initio calculations on electron configurations of trans-einsteinium elements would be to compare atomic properties such as the first ionization potential or the atomic excitation schemes, rather than chemical properties. However, since the production rates of the trans-einsteinium nuclides are low very powerful experimental methods are required to obtain such data. In addition, the experimental methods must yield reliable results even if the half-lives are short and no excited atomic levels are known. The ion-guide detected resonance ionization spectroscopy (IGRIS) method, developed at Mainz University, meets these requirements. Moreover, it provides the option to study nuclear properties such as spins, charge radii and moments. It is based on laser spectroscopy and will be described in the following.

Laser spectroscopy is a very sensitive method for the investigation of nuclear properties of rare radioactive species [50]. Many experimental results have been obtained at ISOLDE (CERN) with the collinear laser spectroscopy. In special cases only about 100 ions / s are required for a high-resolution hyperfine spectroscopy which yields information on the nuclear spin, the nuclear moments and the change of the nuclear charge radius as functions of the neutron number. For production rates of less than 100 ions / s the radiation detected resonance ionization spectroscopy (RADRIS) technique [51] in a buffer gas cell has been shown to be a powerful method. This method can be employed for the investigation of radioactive nuclides with half-lives as short as 1 ms and produced with rates of less than 10 ions / s, as has been demonstrated with the spectroscopic investigations at the  $^{240\text{f},242\text{f}}\text{Am}$  fission isomers [52,53]. However, the detection of the ionization process by observing radioactive decay limits the applicability of this method to nuclides with half-lives less than a few minutes. Therefore, the method has been developed further into IGRIS. In this method the radioactive decay detection has been replaced by mass-selective direct detection of the ions, as in the ion-guide quadrupole mass separation technique [54] in which the ions leaving the buffer gas cell are separated from the gas jet and mass analyzed in a quadrupole mass filter [55]. The combination of resonance ionization spectroscopy and mass analysis of the extracted ions provides information on both the nuclear charge number and the mass number of the ions. A very compact IGRIS apparatus has been constructed and successfully tested at Mainz University [56]. The combination of this technique with SHIPTRAP presents the unique possibility of investigating atomic, nuclear and ion chemical properties in the region of super heavy elements.

Knowledge of the first ionization potentials itself provides detailed insight into relativistic effects and the chemical behavior of these elements. However, so far, ionization potentials have been measured in laboratory experiments only for elements up to einsteinium ( $Z = 99$ ) [57] with macroscopic samples of more than  $10^{10}$  atoms. The experiments on trans-einsteinium elements are particularly difficult since no

excited atomic states are known. Nevertheless, it is proposed to study the atomic and nuclear structure of these heavy elements with IGRIS at SHIPTRAP. A feasibility study will be performed for fermium ( $Z = 100$ ) at the MPI für Kernphysik in Heidelberg. At SHIPTRAP the elements Md ( $Z = 101$ ), No ( $Z = 102$ ), and Lr ( $Z = 103$ ) with production cross sections in the  $\mu\text{b}$  range can be investigated.

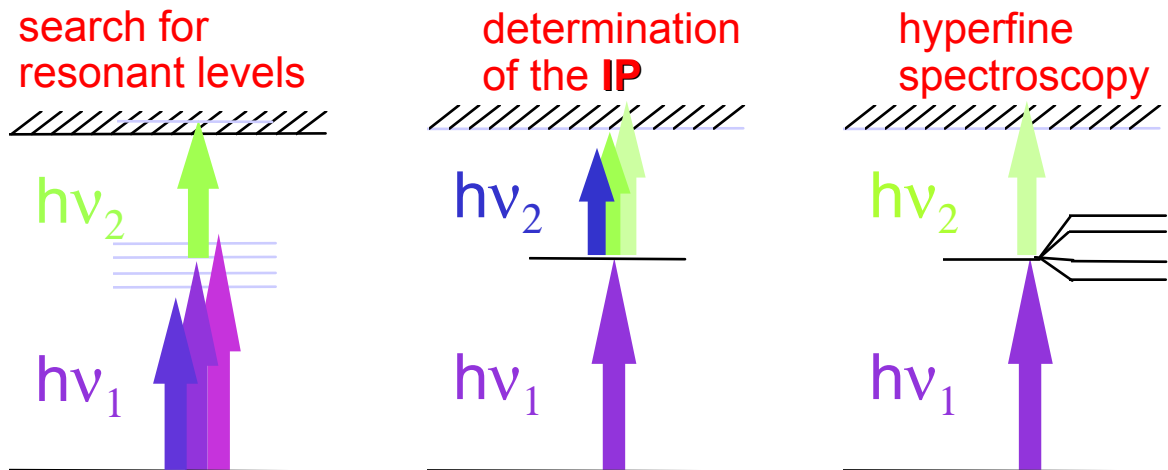


Figure 7. Schematic representation of the atomic excitation processes of importance to the optical spectroscopy of trans-einsteinium elements.

When excited atomic states of the trans-einsteinium elements are known the hyperfine structure of suitable transitions can also be studied with IGRIS at SHIPTRAP. In this way, nuclear ground-state properties like spin, magnetic dipole moment, electric quadrupole moment and charge radii can be determined. Such data will enable a stringent test of the application of nuclear models to the heaviest nuclei. This technique is applicable if the production rates are in the order of 10 ions / s, numbers which seem to be reachable for the above-mentioned cases. Figure 7 illustrates the different atomic excitation processes involved in the proposed experiments.

Collinear laser spectroscopy with fluorescence detection [50] on a fast beam formed after the SHIPTRAP system can be an alternative, or even a complementary technique, to the IGRIS method. Its resolution is much better but at the expense of a significantly lower sensitivity. However, advantage can be taken of the pulsed character of the beam to reduce the signal background.

## 6. Time schedule

### **Spring 1998 :**

Study of the stopping chamber and extraction process

Study of the ion cloud produced by stopping a SHIP beam in helium / argon

Study of the design requirements needed of a stopping chamber for RIS ions

### **Summer 1998 :**

Design and fabrication of the first stopping chamber

Design of the bunching system

### **Autumn 1998 :**

Testing of the stopping chamber

Fabrication of parts for the bunching system

Design of the collection/purification trap

Ordering of the superconducting solenoid for the collection/purification trap

### **Winter 1998-1999 :**

Assembly and testing of the bunching system

Fabrication of parts for the collection/purification trap

### **Spring 1999 :**

Assembly and testing of the collection/purification trap

### **Summer/autumn 1999 :**

Assembly and testing of complete system

## 7. Estimated capital costs

<b>The stopping chamber(s)</b> (gas handling system; gas purifier; electrical supplies & controls; fittings, materials and supplies) :	60 000 DM
<b>The extraction chamber</b> (vacuum pumps; vacuum system components; programmable wave-form generator; radiofrequency amplifier; electrical supplies & controls ; materials and supplies ) :	130 000 DM
<b>The buncher system</b> (vacuum pumps; vacuum system components; programmable wave-form generator; radiofrequency amplifier; computer controlled pulse generators; high-voltage switching supplies; miscellaneous electronic components; materials and supplies):	150 000 DM
<b>The collector/purification system</b> (superconducting solenoid; vacuum system components; programmable wave-form generator; computer controlled pulse generators; high-voltage switching supplies; miscellaneous electronic components; materials and supplies):	300 000 DM
<b>Control computer and interface system</b>	30 000 DM
<b>Installation costs</b> (electrical components; gas system components; structural materials)	30 000 DM
<b>Total</b>	<b>700 000 DM</b>

Note : For the modification of the ion optics and the target of SHIP in view of the planned intensity upgrade of the system, 236 000 ECU will be provided by the European Community (Network "Access to Large Facilities").

## 8. References

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